Exchanges

- Selected Research Papers -

Ocean state estimation in support of CLIVAR and GODAE[1]

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1. Introduction

The ocean is changing vigorously on a wide range of time and space scales. This variability leads to substantial problems in observing and modelling (simulating) the rapidly changing flow field, the ocean's temperature distribution, and more generally the consequences of those changes for climate. Prototype ocean observing systems, which are now in place as a legacy of programmes such as the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean Global Atmosphere Programme (TOGA), aim at measuring and detecting large-scale changes of various quantities in the ocean, such as temperature, salinity, velocity, nutrients, tracers, etc. The present coverage of interior temperature and salinity measurements will significantly increase with the launch of the global ARGO float programme, which in combination with the complementary high-quality altimetric satellite data will be the backbone of a climate observing system. However, in spite of those unprecedented data, the interior of the ocean will remain fairly undersampled, and much of our understanding and inferences about the ocean's role in shaping our climate will come from the additional information provided by numerical ocean general circulation models.

Among the goals of the present ocean and climate research are therefore to measure, understand, and eventually predict these variations by combining ocean data and ocean models. Today high-resolution simulations of the ocean are performed on a routine basis with realistic coastlines, bottom topography, and surface forcing. By combining ocean observations with those state-of-the-art models, one can obtain an analysis of the time-varying ocean that, when taking into account errors in data and models, must necessarily be more complete and better than the information from either of them alone. This is the heart of ocean state estimation (often referred to as "data assimilation") which has at its goal to obtain the best possible description of the changing ocean by forcing the numerical model solutions to be consistent with the observed ocean conditions. This by itself is a very cost-effective way to obtain a fairly complete description of the changing ocean from a limited set of observations. But at the same time it also identifies model components that need improvement, including surface forcing fields, and guides us as to where we need to extend the observing system to improve the estimated ocean state.

2. Ongoing Activities

Because of the fundamental importance of understanding the present and future states of the ocean, two consortia on ocean modelling and state estimation were supported recently through the US National Ocean Partnership Program (NOPP) with funding provided by the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Office of Naval Research (ONR). Those two modelling and assimilation activities are described in detail in Stammer and Chassignet (2000). One of them is called "Estimation of the Circulation and Climate of the Ocean" (ECCO). This ECCO consortium builds on existing efforts at the Massachusetts Institute of Technology (MIT), the Jet Propulsion Laboratory (JPL), and the Scripps Institution of Oceanography (SIO), with additional partners at the Southampton Oceanographic Centre (SOC) and the Max-Planck Institut für Meteorologie (MPI) in Hamburg. Its primary goal is to provide the best possible dynamically consistent estimates of the ocean circulation, which can serve as a basis for studies of elements important to climate (e.g., heat fluxes and variabilities). This model-based synthesis and analysis of the large-scale ocean data set will enable a complete (i.e., including aspects not directly measured) dynamical description of ocean circulation, such as insights into the natures of climate-related ocean variability, major ocean transport pathways, heat and freshwater flux divergences (similar for tracer and oxygen, silica, nitrate), location and rate of ventilation, and of the ocean's response to atmospheric variability.

The ongoing ocean state estimation is based on the MIT GCM (Marshall et al., 1997) and two parallel optimization efforts: the adjoint method (Lagrange multipliers or constrained optimization method), exploiting the Tangent-linear and Adjoint Compiler (TAMC) of Giering and Kaminsky (1997) as described in Marotzke et al. (1999), and a reduced state Kalman filter, e.g.,

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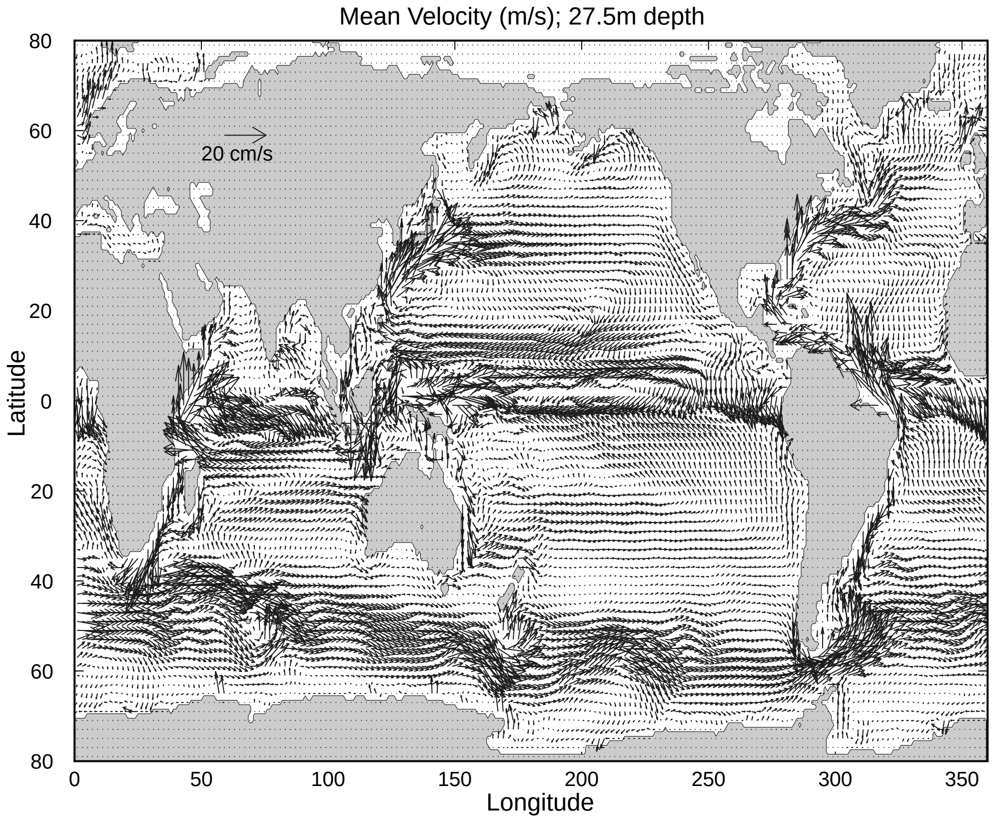

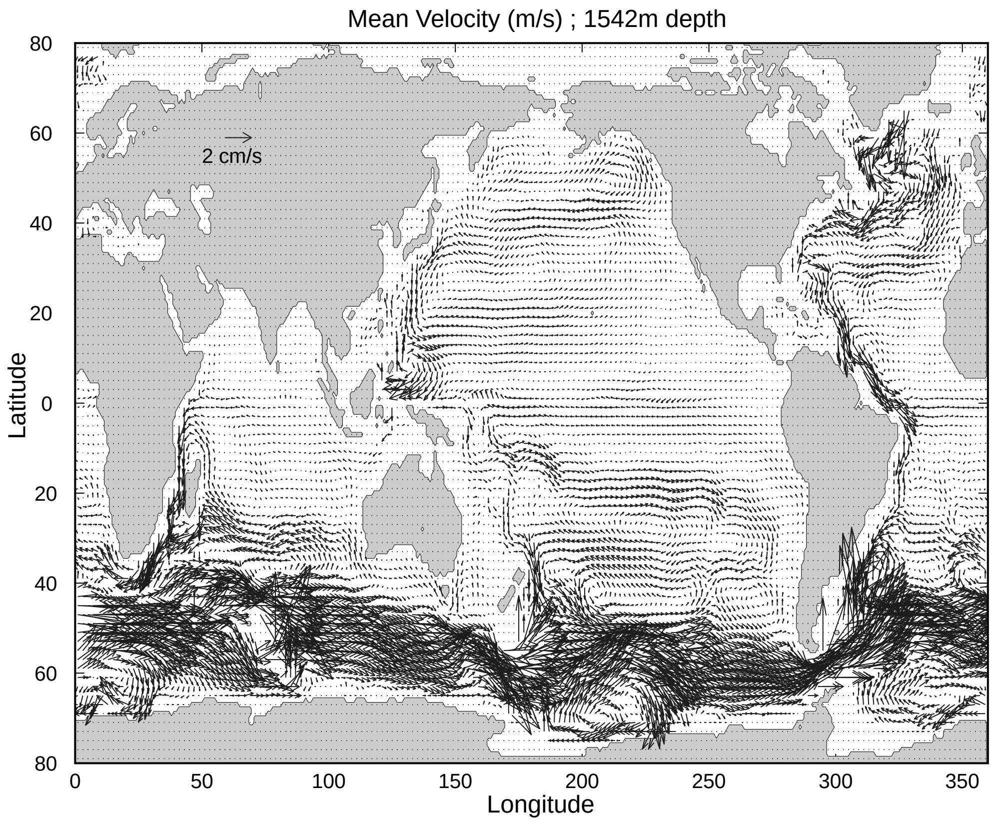

Figure 1: The estimated mean velocity fields at 27 and 1542 m depth show all major current systems. Due to the low model resolution, they are necessarily overly smooth.

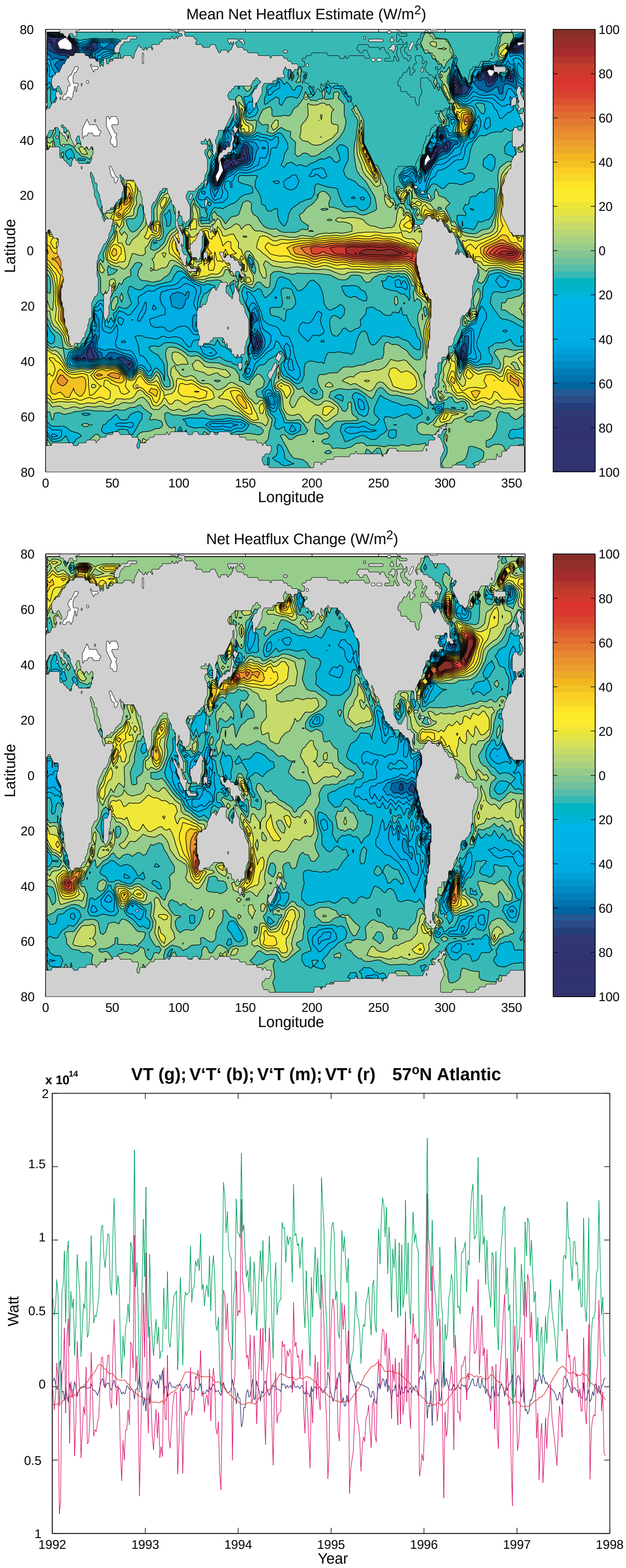

Figure 2: The mean net surface heat field as it results from the optimisation is displayed in the upper panel. Its mean change relative to the prior NCEP fields is provided in the middle pannel. All resulting modifications of the net NCEP heat fluxes, which are of the order of 20 Wm^{-2} over large parts of the interior oceans and reach 80 Wm^{-2} along the boundary currents, are consistent with our prior understanding of NCEP heat flux errors.

Bottom panel: The estimated net fluxes H_q is shown across 25° N in the North Atlantic (green line). It can be decomposed in to a mean and a time varying part

$$H_q(t)= \iint \bar{v}\bar{\theta}\,dzdx + \iint v'\theta'\,dzdx + \iint \bar{\theta} v'\,dzdx + \iint \bar{v}\theta'\,dzdx$$

where the bar indicates the time-average. The latter three terms are displayed as blue, magenta and red lines, respectively.
The last term in θ' gains importance towards high latitudes and is responsible for almost all changes on the seasonal cycle in mid and high latitudes. The second and third terms involving v' are somewhat larger but to some extend cancel each other during winter seasons, especially in high latitudes where they are also smaller but in phase during summer time. Towards low latitudes, most of the variability in the meridional heat flux comes from the $v'\bar{\theta}$ term, while the two other terms are very small.

Fukumori et al. (1999). Those data assimilation activities can be summarized as finding a rigorous solution of the model state $\boldsymbol{x}$ over time t that minimizes in a least-squares sense a sum of model-data misfits and deviations from model equations while taking into account the errors in both.

First such results of a global ocean state estimation procedure are summarized in Stammer et al. (2000). Data currently employed in the optimization include the absolute and time-varying T/P data from October 1992 through December 1997, SSH anomalies from the ERS-1 and ERS-2 satellites, monthly mean sea-surface temperature data (Reynolds and Smith, 1994), time-varying NCEP reanalysis fluxes of momentum, heat, freshwater, and NSCAT estimates of wind stress errors. Monthly means of the model state are required to remain within assigned bounds of the monthly mean Levitus et al. (1994) climatology. To bring the model into consistency with the observations, the initial potential temperature (θ) and salinity (S) fields are modified, as well as the surface forcing fields. Changes in those fields (often referred to as "control" terms) are determined as a bestfit (in a least-squares sense) of the model state to the observations and their uncertainties over the full data period.

A few representative ECCO results are summarised in Fig. 1 and Fig. 2. The estimated mean velocity field at 27 and 1542 m depth (Fig. 1) shows all major current systems. But with the low model resolution, they are necessarily overly smooth. The mean net surface heat and freshwater flux fields as they result from the optimization are displayed in the upper row of Fig. 2 (page 15). Their mean change relative to the prior NCEP fields are provided in the middle part of the figure. Ocean transports of all quantities are very energetic and variable. As an example we show here the net northward heat transport across 25°N in the North Atlantic as it results from the optimized model state. The estimated time-varying model state, model transports and consistent surface flux fields will be the basis for a wide variety of climate and societal applications. Many interdisciplinary applications are already under way or have begun recently, including studies of the ocean's impact on the earth angular momentum budget (Ponte et al., 2000).

3. Outlook

Now ongoing computations move toward a 6-year estimate of the time-evolving ocean circulation (1992 through 1997) with 1° spatial resolution that uses all major WOCE data sets as constraints, and that has build in a complete mixed layer model (Large et al., 1994) and an eddy parameterization scheme (Gent and McWilliams, 1990). It is anticipated that, in two to three years, the project will be able to address the US CLIVAR and GODAE related objective of depicting the time-evolving ocean state with spatial resolution up to 1/4° globally and with substantially higher resolution in nested regional approaches which are required for quantitative studies of the ocean circulation. Complementary to this, a 50 year long re-analysis experiment is anticipated but with only a 1° spatial resolution that coincides with the NCEP/NCAR reanalysis period.

A major issue for the ECCO consortium, and generally for the wider oceanographic community, is the way in which the need for computer resources has now outstripped their availability. No short-term solution to the computer resource bottleneck is as yet visible. However, there is an ongoing NOPP activity aiming to organise a substantial increase and improvement in computational infrastructure for oceanographic research (OITI). If successful, it will have a profound impact not only on many future NOPP modelling and assimilation activities; it will be an important step toward reaching GODAE and CLIVAR goals.

The ECCO estimated time-varying model state and consistent surface flux fields from the entire estimation period can be accessed via the web page **http://www.ecco.ucsd.edu**/.

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